Establishing a Hybrid Plasma Environment Simulation Facility

Georg Herdrich[1], Rene Laufer[2], Michael Dropmann[3], Roland A. Gabrielli, Truell W. Hyde, Hans-Peter Roeser

Institute of Space Systems (IRS), University of Stuttgart, Raumfahrtzentrum Baden-Wuerttemberg, Pfaffenwaldring 29, 70569 Stuttgart, Germany

Center for Astrophysics, Space Physics and Engineering Research (CASPER), Baylor University, One Bear Place #97310, Waco, TX 76798-7310, USA

[1]herdrich@irs.uni-stuttgart.de; [2]rene_laufer@baylor.edu; [3]michael_dropmann@baylor.edu

Abstract

Over the past decade, investigations into dusty plasmas have improved our understanding of protoplanetary environments, moons (including Earth's Moon), ring systems and comets. They have also been instrumental in the advancement of semiconductor development, nanofabrication and are proving of great interest in the dust contamination problems found within nuclear fusion devices such as ITER. Recently, the Lunar Exploration Analysis Group (LEAG) identified a need for research on the lunar dust and plasma environment. As part of its goal to expand current research capability in this area, the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University, Texas, and its partner the Institute of Space Systems (IRS, in German: Institut für Raumfahrtsysteme), Universität Stuttgart, Germany, established two highly flexible plasma environment simulation facilities. The facility at Baylor University and the associated research will be subject of this Paper.

As hybrid facility it consists of an adjustable, inductively heated plasma generator (IPG) which can be coupled to a variety of systems allowing the introduction of the additional components (e.g. levitating or accelerating dust, UV light) necessary to accurately simulate a given plasma environment. Potential research for such a device includes investigations of dusty plasma effects on the surface of planets, moons and comets, interactions between dusty plasma and spacecraft materials and components, in-situ instrumentation development and testing as well as research and development for terrestrial applications such as the examination of the dust and heat fluxes in fusion reactors.

Keywords

Inductively Coupled Plasma Source; Natural Plasma; Man-Made Plasma; Dusty Plasma; Plasma Simulator; Environment Simulation

Introduction

In 2006 in response to NASA's request "to provide guidance on the scientific challenges and opportunities enabled by a sustained program of robotic and human exploration of the Moon during the period 2008-2023 and beyond", the National Research Council (NRC) established the Committee on the Scientific Context for Exploration of the Moon. This committee prepared a report, titled The Scientific Context for Exploration of the Moon [1], to provide scientific input to NASA facilitating the planning of a "comprehensive, well-validated, and prioritized set of scientific research objectives for a program of exploration of the Moon". Within the eight scientific concepts and 35 scientific goals, the lunar plasma environment was identified as an area of research where significant gaps in our current understanding remain.

Improving our understanding of the space plasma environment at the lunar surface and in lunar orbit is essential for appropriately preparing and providing subsequent support for robotic and human exploration. Properly defining such a dust and plasma environment requires both laboratory experiments and numerical modelling.

The Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University, Texas, and its partner the Institute of Space Systems (IRS), Universität Stuttgart, Germany, plan to address the above through the characterization and validation of a flexible plasma facility IPG6-B [2] at Baylor University, which is a twin facility to the IPG6-S [3] facility in Stuttgart at IRS. IPG is short for Inductively heated Plasma Generator. The plasma source design is derived from previous IRS designs, which allow the creation of high enthalpy plasma jets. Through operation of the plasma source under low gas flow

rates, low density plasmas of e.g. Hydrogen can be created which have relevance for the simulation of the lunar plasma environment. Similar environments such as those found near asteroids and comets or even parts of the solar plasma could also be assessed. Low density Oxygen plasmas can also be created in order to create conditions relevant for spacecraft in low earth orbit. Finally, since the plasma source design is very close to those used for atmospheric entry studies at the IRS, it can be used for the simulation of high heat fluxes like those found e.g. in fusion devices.

Approach and Method

An assessment of all relevant lunar plasma environmental data with a particular emphasis on in-situ data (for example, the data collected by the Lunar Prospector mission) will be the starting point for studies on the lunar plasma environment. The resulting database will provide the boundary conditions necessary for properly defining the conditions to be simulated either experimentally employing the proposed plasma facility and/or theoretically using numerical tools already in place at CASPER and its partnering institutions. As mentioned above, a primary goal is to develop the facility in such a manner that it can reproduce various plasma dust environments through the production of relevant plasma densities, mass flow rates and ambient pressures. Once these initial conditions are established, the resulting experimental data can then be characterized using appropriate diagnostic measurements (e.g. Langmuir probes and others).

It is understood that the commissioning, qualification and characterization process for the facility will not necessarily allow a match for all plasma conditions that need to be reproduced. However, the proposed experimental plasma source should provide the basis for verification and validation of the numerical tools, which can then in turn be applied to produce data representative of a lunar plasma environment.

CASPER and the IRS established a flexible experimental plasma environment simulation facility through the design and construction of an inductively heated plasma generator based on proven IRS plasma source designs. During the initial phases of this project the focus will be on the qualification and characterization of the plasma source and identification of the operating parameters necessary to produce the desired plasma environments. Lunar environmental simulations will simultaneously be conducted introducing dust, lunar simulant, UV light and/or other known environmental elements. The verification and scaling of these experimental results will be accomplished through theoretical modelling using proven IRS and CASPER algorithms (e.g. box_tree, an N-body model for charged dust). Finally, validation/correlation of all numerical results will be sought to data derived from remote sensing and in-situ experiments on-board former and active space missions and to data from existing models (e.g. data produced by the NASA Lunar Science Institute member team at the Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS), University of Colorado, Boulder).

The reproduction of conditions relevant for natural plasmas, such as the lunar plasmas or any of the solar wind derived plasmas is possible with the currently developed facilities since they can be operated using pure hydrogen as well as even more relevant gas mixtures; by adding the contributions of the noble gases usually found in the solar wind and solar wind derived plasmas, these can be examined as well. The similarity parameters have yet to be identified; this is the subject of current research. It seems evident that similarity of energy is needed - at least to a certain extent. However, for most cases the facilities will not be capable of fully copying the conditions that are given for a typical lunar plasma; for example the inner energy of the facilities' plasma will be significantly higher than the energy of a lunar plasma, which is dominated by the kinetic energy of the particles. Correspondingly, this similarity may result in a comparison of the mass specific enthalpy and an equivalent velocity which then could be compared with the typical particle velocities of natural plasmas. With the estimated order of magnitude for the bulk enthalpy of 0.75 GJ/kg (Will be derived in section IV.) an equivalent velocity of roughly 38 km/s can be derived using equation 1.

$$v = \sqrt{2\varepsilon} \tag{1}$$

Where v denotes the velocity and ε the specific energy or enthalpy. Thus it can be expected that relevant equivalent velocities can be simulated, e.g. for entries into atmospheres of gas giants.

A T_e (n_e)-Diagram for sun derived plasmas in the solar system is shown in Fig. 1. In [4] T_e and n_e data for high enthalpy oxygen plasmas generated with IPG3, which is a high power inductively driven plasma generator at IRS, were derived, in [5] such data were derived

from high enthalpy hydrogen plasmas generated with a hybrid plasma generator consisting of an IPG3 used as second stage for a DC plasma generator.

It can be seen from the limited data base shown that at a minimum the data collected should correspond to known parameters of solar atmosphere plasmas. This result is promising and allows the statement that at least some natural plasmas can be modeled experientially in terms of number densities and temperatures of the electrons by the facility described. However, such conditions will have to be calibrated using suitable measurement techniques in order to extend the data set outlined in Fig. 1.

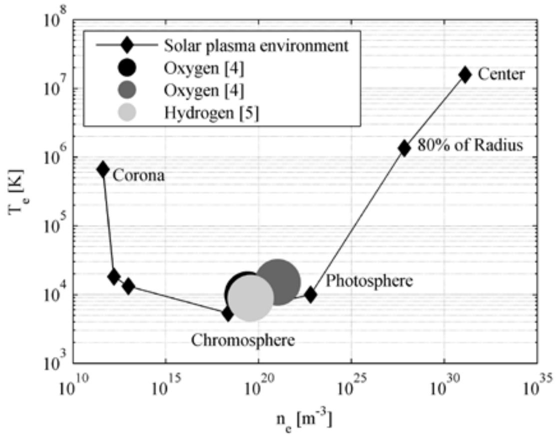

FIGURE 1 $T_E(N_E)$ DIAGRAM FOR SUN DERIVED NATURAL PLASMAS AND DATA FROM HIGH ENTHALPY IPGS

For an overall consideration an equilibrium analysis allows the derivation of the following facts:

- Molecular hydrogen is negligible for temperatures above 6500 K.
- The ionization degree for T = 10 kK would be near to 1 for a pressure of 10 Pa (order of base pressure of the two facilities).
- In [5] electron temperatures on the order of 10 kK are reported in a hybrid (Arcjet + IPG) plasma generator at IRS (on the basis of an analysis).
- The corresponding electron number density is $4 \cdot 10^{19}$ m^{-3} ($p = (n_i+n_e)kT$ with $n_i = n_e$)

Areas of Investigation

The starting point for investigations employing the proposed plasma source are primarily related to the lunar environment and the need to produce the data necessary for a proper understanding of the physics behind various outstanding issues including:

- Investigations into simulated lunar dusty plasma environments and possible associated dusty plasma effects (e.g. dust charging);
- Investigations into lunar regolith simulants and their interaction in lunar plasma environments;
- Validation and improvement of existing lunar simulants;
- Investigations into the interaction between a dusty plasma and spacecraft materials, components, and subsystems as development support for future spacecraft hardware; and
- The development of a test bed along with the measurement techniques necessary for prototype and component testing as development support for future in-situ instrumentation (e.g. CASPER instrument contribution to the planned Stuttgart small Moon orbiter LUNAR MISSION BW1).

In addition there are other obvious fields of work within the area of space plasma environment simulation. Researchers within CASPER have been active both theoretically and experimentally in the study of grain charging within space and terrestrial plasmas for over thirty years. Dust particles immersed within a space plasma environment, such as those found in protostellar clouds, planetary rings or cometary environments, acquire an electric charge [6, 7, 8]. If the ratio of the inter-particle potential energy to the average kinetic energy is high enough the particles can also form a ''liquid'' structure with short-range ordering [9].

A proper understanding of the manner in which such dust particles charge and then interact with the plasma environment (flowing or quiescent) surrounding them is essential to understanding the development of planetary rings, coagulation in presolar environments, cometary tails, particle 'hopping' on the lunar surface or dust mitigation on spacecraft [10, 11, 12, 13, 14]. For example, the initial stage in planetesimal formation is the aggregation of dust, a process which is believed to take place on the relatively short time scale of a few millions of years. Recent astronomical evidence has shown that the dust surrounding newly formed stars emits more efficiently at longer wavelengths as the disk evolves, indicating this coagulating dust may be forming large fluffy aggregates. Therefore in order to fully understand the evolution of the planetesimals developing from the constituent matter within a dusty disk, it is first necessary to understand the manner in

which the dust charges and then interacts with the surrounding plasma.

Additionally, highly ordered lattice structures of charged dust grains (coulomb lattices, coulomb balls, extended vertical strings and others) have recently been observed in laboratory complex plasmas (such plasmas are as well investigated at CASPER) illustrating the need for a more careful experimental treatment determining the charge attained by such grains. For example, when calculating the charge on an individual grain embedded within a dust cloud immersed in a moderate-temperature ambient plasma, the potential at equilibrium cannot in general be taken to be the same on the surfaces of all the constituent grains. This is due to the fact that when charging currents (such as the secondary-electron current) having a dependence on grain size apart from the cross-sectional area are present, the grain surface potential can vary from grain to grain. Since this has direct implications on grain coagulation in protoplanetary disks and gravitoelectrodynamics in planetary rings, experimental data clarifying this process is again desperately needed.

New technical applications for these plasma generators might also be identified, such as the production of electrode layers for fuel cells or the treatment of industrial and organic wastes. More information can be found in [15]. Investigations of dust in fusion reactors are another example for potential spin-off research.

Spin-off Research: Fusion Reactor

The presence of dust in fusion reaction devices has been seen for more than two decades. Particles of various shapes (irregularly shaped flakes to almost perfect spheres) and sizes (nanometers to hundreds of microns), have been observed and their effects investigated [16]. Although different theoretical dust production mechanisms have been suggested, an understanding of the physics behind the production and subsequent motion of this dust is still unclear. With the recent development of ITER, concern over both the magnitude of the dust produced and its impact on the performance and stability of the core plasma continues to grow.

Current theoretical and experimental efforts to understand these processes have been hampered by an incomplete understanding of what are known as plasma-wall-interactions (PWI). Since much of the dust seen in fusion devices to date is probably created due to ablation of the wall surfaces, a better understanding of PWI's is necessary in order to explain the separation / ablation of the dust from plasma exposed surfaces and the mechanism(s) behind its acceleration within the sheath located at the surface of the wall. Additionally, this process is directly linked to edge-plasmas, which play an essential role in the success of fusion devices by establishing the boundary conditions for the plasma core.

A fusion reactor's first wall will be exposed to a heat flux similar to what can be created by the presented system at high gas flow rates. The reactor's core – hot plasma devoid of gas dynamic behaviour – loses power continuously. Particularly in the case of closed magnetic fusion devices which are being investigated for terrestrial power generation in devices such as the ITER-Tokamak, these power losses state the heat flux the first wall has to mitigate [17, 18].

The major participating phenomena are thermal losses, bremsstrahlung, synchrotron radiation and neutron radiation [17, 18]. The latter is irrelevant in the case of advanced aneutronic fusion reactions, yet important for the deuterium-tritium (DT) fuel of first generation fusion power plants for various reasons [17, 18, 19].

Unlike the presented system, there will not be any gas dynamic boundary layer attached to the first wall in the case of terrestrial reactors. Instead there will be a gap between the plasma and the first wall [17, 18, 19]. Thermal losses will mainly consist of occasional runaway plasma particles [19] spilling into the gap. This so called scrape-off layer (SOL) is shown in the poloidal section of a simplified state-of-the-art Tokamak (Fig. 2).

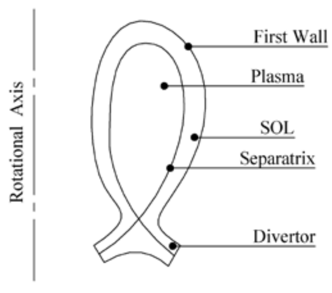

FIGURE 2 POLOIDAL SECTION OF A SIMPLIFIED STATE-OF-THE-ART TOKAMAK

Wall-loading research [17, 19, 20] indicates, that for large areas of the first wall the heat flux will not exceed 2 MW/m^2 for DT (Table 1). However, the particles of the SOL can impact in rather small areas (divertor targets) which are hence exposed to higher loads up to 20 MW/m^2 [19, 20].

During recent studies on fusion propulsion at the Institute of Space Systems of the University of Stuttgart [21, 22], wall loads have been estimated for three idealized geometries with arbitrary dimensions and four fuel reactant couplings. While the values concerning the DT fusion fuel are similar to those mentioned for terrestrial application, those concerning advanced fuels exceed the first considerably (Table 2).

TABLE 1 WALL LOADING LIMITS ACCORDING TO REFERENCES

Reference	Wall loading limit/ [MW/m²]	Note
Reece Roth [17]	2 – 4	Estimation for neutron loading
	0.2 - 0.8	Thermal load estimation (design studies for DT reactors)
	0.6	Assumption on material behaviour (thermal loading)
	2	Engineering studies on material (thermal loading)
	5	Total loading limitation (radiative and thermal loads)
Clark and Reiter [19]	0.15	Average wall load (thermal, ITER study)
	10 – 20	Peak load (thermal, ITER study)
Bolt et al. [20]	0.1 – 10	Pulsed heat flux
	50 – 2000	Thermal shock
	>150	Damage threshold
IPG6 (Fig. 3)	<7	Maximum estimated heat flux on material sample

TABLE 2 WALL LOADS FOR DIFFERENT FUEL COMBINATIONS AND REACTOR GEOMETRIES

	Thermal, radiative wall loading MW/m²		
Reactor	**Sphere**	**Torus**	**Open mirror**
DT 10 m³	0.3, 4.3	0.7, 9.3	1.5, 20
D ³He 10 m³	11, 23	24, 49	51, 105
11B p 10 m³	92, 224	195, 477	421, 1029
³He ³He 10 m³	4209, 10560	8971, 22500	19362, 48550
DT 50 m³	0.5, 7.5	1.2, 16	2.5, 34
D ³He 50 m³	19, 39	41, 84	88, 180
11B p 50 m³	157, 382	334, 815	720, 1759
³He ³He 50 m³	7198, 18050	15340, 38470	33110, 83030
DT 100 m³	0.7, 9.4	1.5, 20	3, 43
D ³He 100 m³	24, 49	51, 105	111, 227
11B p 100 m³	197, 482	421, 1027	907, 2220
³He ³He 100 m³	9068, 22740	19330, 48470	41710, 104600

This is of special interest as at IRS an effusion cooled heat flux probe will be developed, which could also be used for characterization of the presented facility.

In order to analyse the potential of the two facilities to cope with the required heat fluxes a relationship between the load seen by the surface and the mass specific enthalpies that can potentially be produced by the facility must be employed. Here, the relationship of [23] can be used as this is validated in the field of experimental aerothermodynamics. With

$$h = \frac{\dot{q}_{fc}}{K}\left(\frac{p_{tot}}{R_{eff}}\right)^{-1/2} \tag{2}$$

measured radial profiles of the fully catalytic ("fc") heat flux and the total pressure p_{tot} can be conveyed to a mass specific enthalpy h and vice-versa where the constant K is gas (plasma) specific. Reference [23] gives $K = 0.10226\ \mathrm{kWkg(MJm)^{-1}(mPa)^{-1/2}}$ as value for hydrogen plasmas. The parameter R_{eff} is an effective radius of a respective plasma probe that could measure heat flux and Pitot pressure or could be a sample support probe carrying a high temperature material sample. This concept is used for non-spherical bodies and it corresponds to the radius of an equivalent sphere leading to the same velocity gradient at stagnation point. Correspondingly, the effective radius of a non-spherical e.g. blunt body depends on the condition of the incident flow. However, 2.3·R can be used as an estimative value for R_{eff} for typical conditions expected for this facility [24]. For the estimative considerations here this probe would have to be significantly smaller than the discharge channel of the plasma source which is 40 mm and less than 10 mm can be assumed for the radius of this probe ($R_{eff} < 23$ mm). In [4] maximum Mach numbers in the order of 4 to 5 were achieved for an oxygen plasma condition at minimum base pressure of 40 Pa. At an axial distance of 130 mm from the outlet of the inductively heated plasma generator IPG3 a total pressure on the order of 4 hPa was achieved [5]. Using an order of magnitude of 1 hPa as such and a probe radius of 10 mm allows for the calculation of the upper limit of the needed mass specific enthalpy for a required heat flux. However, in future measurement campaigns the facility as such will have to be characterized using adequate measurement techniques like heat flux probes and Pitot pressure probes. In order to assess the radial properties of the plasma jet, however, the diameter of

our fictive probe has to be significantly smaller than the diameter of the discharge channel of IPG6 as this is a coarse measure for the overall plasma jet diameter. Correspondingly the situation is somehow simplified as this leads a reduction of the mass specific enthalpies needed for the task of e.g. reproducing the relevant heat fluxes for the investigation of fusion reactor high temperature blanket materials.

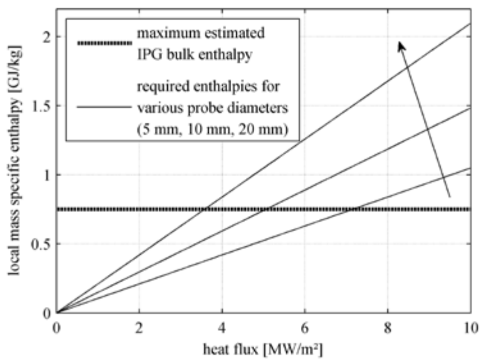

FIGURE 3 ASSESSMENT OF THE ACHIEVABLE HEAT FLUXES IN THE HYDROGEN PLASMA ENVIRONMENT OF IPG6

Fig. 3 shows the resulting mass specific enthalpies for hydrogen with p_{tot} = 1 hPa for the probe radii 20 mm (upper limit of enthalpy), 10 mm and 5 mm. In addition, the plasma power has been estimated using a 50% coupling efficiency (7.5 kW for the IPG6-B facility that has a maximum power of 15 kW). Such efficiencies can be achievable as outlined in [4]. With an assumed hydrogen mass flow rate of 10 mg/s the mass specific bulk enthalpy of the facility can be estimated leading to an order of 0.75 GJ/kg. The mass flow rate is derived from the experiences with TIHTUS [15], a hybrid plasma device consisting of a DC plasma generator and an IPG3 in series. Here, mass flow rates in the order of magnitude of 300 mg/s (hydrogen) were applied (leading to 70 MJ/kg [5]) at power levels of 50 kW. IPG3 has a cross-sectional area for the discharge channel which is almost a factor of four larger compared to IPG6 such that the 10 mg/s as order of magnitude are realistic. The obtained value for the enthalpy, however, is a bulk enthalpy and typical IPG devices as such usually produce radial profiles for properties such as the local mass specific enthalpy. Therefore, the maximum of local specific enthalpy in the plasma jet can be significantly higher than the bulk enthalpy which can rather be considered as an effective mass specific enthalpy. As a conclusion it can be said that IPG6 should be capable to produce heat fluxes on the order of 5 MW/m^2 and even more using a hydrogen plasma environment. However, the required diagnostic equipment that still has to be developed must be small in diameter for the derivation of adequate radial profiles in the jet. Though practical limits concerning the size have to be taken into account as the cooling of the probe gets more difficult the smaller the probe is.

Environment Simulation Facility and Inductively-Heated Plasma Generator

The development of the inductively heated Plasma Generator (IPG) enabled the electrode-less generation of high enthalpy plasmas, such as those found in plasma wind tunnels, for the simulation of atmospheric entry in the development, investigation and qualification of heat shield materials. The electrode-less design allows operation with reactive gases while measurements of the thermal plasma powers, coil currents, operational frequencies, electromagnetic fields, heat fluxes on probes, Pitot pressures and Mach numbers allow for extensive characterization of both the plasma generators' operational behavior and the plasma flow conditions. Additionally, the IPG design enables the generation of realistic plasma conditions, as it is highly flexible concerning the working gas mixture. Even carbonaceous, dusty or oxygen-containing working gases, which have a destructive influence on electrode based plasma generators, can be used [4, 25]. IPG designs have been used at IRS since the 1990's across a number of research fields, including use of a hydrogen-propelled IPG as the second stage of a hybrid thruster system.

Inductively heated plasma generators use the transformer principle to create a plasma. A RF-current is fed into a coil inducing a strong electric field in the plasma which acts like the secondary coil of the transformer. The plasma then gets heated by the resulting electric current. A rough scheme of the IPG6 design is shown in Fig. 4.

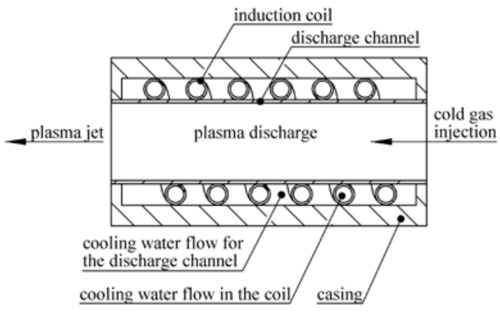

FIGURE 4 WORKING PRINCIPLE OF AN INDUCTIVELY HEATED PLASMA GENERATOR

Cold gas is injected into one side of the plasma generator. By adding an azimuthal component to the gas flow, stabilization of the plasma can be achieved. After injection, the gas enters the quartz tube discharge channel, which can withstand both high temperatures and reactive gases. The discharge channel is surrounded by a water jacket to facilitate cooling. Further it is surrounded by the induction coil, which heats the plasma.

The IPG6 test facilities at the University of Stuttgart (IPG6-S) and at Baylor University (IPG6-B; Fig. 5) are based on the design of the before mentioned IPGs at IRS. The general setup for both facilities is very similar and can be broken down to the subsystems shown in Table 3. For a detailed technical description see [26].

TABLE 3 SUBSYSTEMS OF THE IPG6 FACILITIES

Subsystem	IPG6-S	IPG6-B
Plasma generator	IPG6	IPG6
RF Generator	Himmelwerk HGL 20-4B P_{max}=20 kW f=approximately 4 Mhz (depends on IPG Impedance)	SurePower® QL 15013 A P_{max}=15 kW f=13.56 Mhz L-type tuning network for impedance matching
Vacuum chamber	Cylindrical chamber of 40 cm diameter and length	Cylindrical chamber of 1 m diameter and 2 m length
Vacuum pump	Rotary vain pump with a pumping speed of 400 m^3/h Base pressure: approx. 3 Pa	Two stage vacuum system of a rotary vain pump and a roots pump with a total pumping speed of 160 m^3/h Base pressure: approx. 1 Pa
Water cooling system	Closed circuit with 250 l water	Closed circuit with 250 l deionized water
Diagnostics	Injector pressure Chamber pressure Pitot probe Current monitor IPG cooling Cavity Calorimeter	Chamber pressure Pitot probe Cavity calorimeter Oxygen sensor system

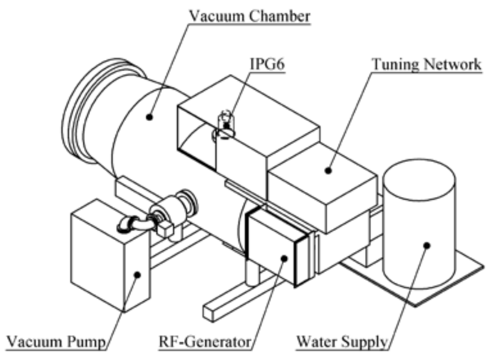

FIGURE 5 SETUP OF THE IPG6-B FACILITY

Several additional modifications to the test facilities are planned in order to extend the research possibilities. Initially, additional diagnostics will be developed and installed in order to increase characterization capabilities. These will include a miniaturized heat flux probe, a Langmuir probe, a side arm for catalysis experiments and optical equipment for emission spectroscopy. An improved vacuum system to decrease the base pressure for low density experiments and a higher pumping speed to keep the pressure at low levels for experiments with high volume flow rates may also be added. Finally, the IPG6-B test facility will be equipped with a dust accelerator (Light Gas Gun) in order to introduce dust (e.g. lunar simulant) at high velocities into the vacuum chamber.

Conclusions

Two plasma facilities, IPG6-S and IPG6-B, have been established at the Institute of Space Systems (IRS), University of Stuttgart, Germany, and the Center for Astrophysics Space Physics and Engineering Research (CASPER), Baylor University, Texas. These facilities allow the generation of a wide range of plasma conditions which can be used to assess various fields of research. These are for example the generation of plasma conditions which can be used to validate numerical tools for the simulation of plasma conditions at the lunar surface. The integration of a Light Gas Gun (LGG), a dust accelerator, into the IPG6-B facility will further add the capability to introduce high velocity dust particles into the plasma having relevance for the study of lunar conditions and for small bodies without atmospheres like asteroids and comets. A second field of research addresses the high heat fluxes seen in fusion devices. First estimations show that these test facilities will be capable of creating representative heat fluxes. Further the LGG will allow the simulation of high velocity

dust particles, which pose a known problem in current fusion devices. Finally experiments concerning catalysis, which can be conducted using a diffusion-based side-arm, and the investigation of plasma radiation will be undertaken. Both facilities have begun operation and are currently undergoing initial characterization experiments.

REFERENCES

[1] National Research Council, The Scientific Context for Exploration of the Moon, Washington, D.C., USA: The National Academies Press, 2007.

[2] Dropmann, M., "Numerical Analysis, Set-up and Qualification of a Hybrid Plasma Simulation Facility", Diploma thesis, IRS-11-S56, Institute of Space Systems (IRS), University of Stuttgart, Germany, 2012

[3] Dropmann, M., "Development and Set-up of an Inductively Heated Plasma Source for Basic Investigations", Student Research Project, IRS11-S-10, Institute of Space Systems (IRS), University of Stuttgart, Germany, 2011

[4] Herdrich, G., Petkow, D., "High Enthalpy, Water-cooled and Thin-Walled ICP Sources: Characterization and MHD-Optimization", Cambridge Journal of Plasma Physics, vol. 74, part 3, pp. 391-429, 2007.

[5] Boehrk, H., "Zur induktiven Nachheizung einer Überschallwasser-stoffströmung", Dissertation, Institute of Space Systems (IRS), Stuttgart, Germany, 2009.

[6] Barge, L., Matthews, L. S., Hyde, T. W., "A Model of Coagulation in Dust Clouds During Grain Charging", Advances in Space Research, vol. 34, no. 11, pp. 2384-2389, 2004.

[7] Matthews, L. S., Hyde, T. W., "Charging and Growth of Fractal Dust Grains", IEEE Transactions on Plasma Science, vol. 36, no. 1, pp. 310-314, 2008.

[8] Matthews, L. S., Hyde, T. W., "Effects of the Charge-Dipole Interaction on the Coagulation of Fractal Aggregates", IEEE Transactions on Plasma Science, vol.32, no. 2, pp. 586-593, 2004.

[9] Morfill, G. E., Annaratone, B. M., Bryant, P., Ivlev, A. V., Thomas, H. M., Zuzic, M., Fortov, V. E.,"A Review of Liquid and Crystalline Plasmas – New Physical States of Matter?", Plasma Phys. Control. Fusion, vol 44, pp. B263-B277, 2002.

[10] Nazzario, R., Orr, K., Covington, C., Kagan, D., Hyde, T. W., "Kuiper Binary Object Formation", Advances in Space Research, vol. 40, pp. 280–283, 2007.

[11] Nazzario, R., Hyde, T. W., Barge, L., "Dust Grain Orbital Behavior Around Ceres", Advances in Space Research, vol. 31, no. 12, pp. 2591-2598, 2003.

[12] Nazzario, R., Hyde, T. W., "Dust Grain Orbital Behavior Around Neptune", Advances in Space Research, vol. 29, no. 9, pp. 1271-1276, 2002.

[13] Matthews, L. S., Hyde, T. W., "Charged Grains in Saturn's F Ring: Interactions with Saturn's Magnetic Field", Advances in Space Research, vol. 33, no. 12, pp. 2292-2297, 2004.

[14] Matthews, L. S., Hyde, T. W., "Gravitoelectrodynamics in Saturn's F Ring: Encounters with Prometheus and Pandora", Journal of Physics A: Mathematical and General, vol. 36, issue 22, pp. 6207-6214, 2003.

[15] Herdrich, G., Auweter-Kurtz, M., "Inductively heated Plasma Sources for Technical Applications", Institute of Space Systems (IRS) and Steinbeis Transfer Centre Plasma and Space Technology (STC PRT), Vacuum Journal, vol. 80, pp. 1138-1143, 2006.

[16] Creel, J., Carmona-Reyes, J., Kong, J., Hyde, T. W., Particulate Contamination Within Fusion Devices and Complex (Dusty) Plasmas, IEEE International Conference On Plasma Science, 2007, Conference Record - Abstracts, 5P37, p. 618.

[17] Reece Roth, J., Introduction to Fusion Energy, Charlottesville, Virginia: Ibis Publishing, 1986.

[18] Schumacher, U., Fusionsforschung - Eine Einführung, Darmstadt, Germany: Wissenschaftliche Buchgesellschaft, 1993.

[19] Clark, R. E. H., Reiter, D. H., Nuclear Fusion Research - Understanding Plasma-Surface Interactions, Berlin, Heidelberg, Germany:Springer, 2005.

[20] Bolt, H., Hoven, H., Kny, E., Koizlik, K., Linke, J., Nickel, H., Wallura, E., "Plasma Induced Material Defects and Threshold Values for Thermal Loads in High Temperature Resistant Alloys and in Refractory Metals for First Wall Application in Fusion Reactors",

Report, Kernforschungsanlage Jülich GmbH, Institut für Reaktorwerkstoffe, Germany, 1986.

[21] Petkow, D., Herdrich, G., Laufer, R., Gabrielli, R., Zeile, O., "Comparative Investigation of Fusion Reactions for Space Propulsion Applications", Transactions of the Japan Society for Aeronautical and Space Sciences, Space Technology Japan, vol. 7, no. ists26 (ISTS Special Issue: Selected papers from the 26th International Symposium on Space Technology and Science), 2009.

[22] Petkow, D., Gabrielli, R., Herdrich, G., Laufer, R., Roeser, H.-P., "Generalized Lawson Criterion for Magnetic Fusion Applications in Space", Fusion Engineering and Design, vol. 87, issue 1, pp. 30-38, 2010.

[23] Marvin, J. G., Pope, R. B., "Laminar Convective Heating and Ablation in the Mars Atmosphere", AIAA Journal, vol. 5, no. 2, pp. 240–248, 1967.

[24] Auweter-Kurtz, M., Herdrich, G., Loehle, S., "Messverfahren Fuer Stroemende Plasmen", Lecture manuscript, Institute of Space Systems (IRS), Stuttgart, Germany 2010

[25] Nawaz, A., Herdrich, G., "Impact of plasma Tube Wall Thickness on Power Coupling in ICP", Plasma Sources Sci. Technol., vol. 18, no. 4, 045018, 2009.

[26] Dropmann, M., Herdrich, G., Laufer, R., Puckert, D., Fulge, H., Fasoulas, S., Schmoke, J., Cook, M., Hyde, T.W., "A New Inductively Driven Plasma Generator (IPG6) – Setup and Initial Experiments", IEEE Transactions on Plasma Science, Special Issue – Dusty Plasmas 2013, accepted.

Georg Herdrich is research scientist and senior lecturer at the Institute of Space Systems of the Univ. Stuttgart and head of the plasma wind tunnels and electric propulsion group. He is also managing director of the Steinbeis Transfer Center Plasma and Space Technology, visiting faculty at Tokyo University and adjunct associate professor at Baylor University. He received his diploma and Ph.D. in aerospace engineering from Univ. Stuttgart. His research interests include atmospheric entry simulation and technology, plasma technology, electric propulsion and in situ sensor systems for atmospheric entry. In 2012 he absolved his habilitation.

Rene Laufer is associate research professor at the Center for Astrophysics, Space Physics and Engineering Research (CASPER) and head of the Space Science Lab of CASPER. He received his diploma in aerospace engineering from Technical Univ. Berlin and his Ph.D. from Univ. Stuttgart. He was involved in planetary missions at the DLR-Institute of Space Sensor Technology and Planetary Exploration and later small satellite project manager and lecturer at the Institute of Space Systems, Univ. Stuttgart. His research interests include small satellites, lunar and planetary exploration, lunar bases, ISRU, dust and plasma, small bodies, remote sensing, systems engineering, education and public outreach.

Michael Dropmann is research associate at the Center for Astrophysics, Space Physics and Engineering Research (CASPER), member of the Space Science Lab of CASPER and a Ph.D. candidate at the Institute of Space Systems of the Univ. Stuttgart. He received his diploma in aerospace engineering from Univ. Stuttgart. His research interests include plasma facility design, plasma surface interactions and space sciences.

Roland Antonius Gabrielli is research associate, Ph.D.-student and junior lecturer at the Institute of Space Systems of the University of Stuttgart. He has diploma degrees from University of Stuttgart and the Institut Supérieur de l'Aéronautique et de l'Espace of Toulouse (formerly SupAéro).

His research interests include advanced propulsion concepts, nuclear thermal and fusion propulsion, power provision systems for space, and social aspects of advanced technologies.

Truell Hyde is vice provost for research at Baylor University, director of the Center for Astrophysics, Space Physics and Engineering Research (CASPER) and professor of physics. He received his B.S. in Physics and Mathematics from Southern Nazarene University and his M.S. and Ph.D. from Baylor University. His research interests include meso- and nanoscale physics, complex plasma physics, protoplanetary and protostellar development, ring/disk systems, Kuiper belt objects, gravitoelectrodynamics, accretion shock studies, and hypervelocity impact studies.

Hans-Peter Roeser is director of the Institute of Space Systems (IRS) and professor of aerospace engineering at Univ. Stuttgart. He received his diploma and Ph.D. in physics from the Friedrich-Wilhelms-Univ. Bonn. He was professor at the Max-Planck-Institute for Radioastronomy and at the Technical Univ. Berlin as well as director of the DLR-Institute of Space Sensor Technology and Planetary Exploration. His research interests include space applications, remote sensing, sensor systems, small satellites, infrared astronomy, heterodyne spectroscopy, nanostructures and high temperature superconductors.